Repercussions on Concrete Permeability Due to Recycled Concrete Aggregate

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Synopsis: This paper presents an experimental analysis of recycled concrete (RC) in which the natural aggregates are replaced by recycled concrete aggregates (RCA). This experimental program covers the specifications of the aggregates employed, together with that of the concrete that is manufactured with them.

The considerable effect on the permeability of RC that is produced by the use of RCA is described and discussed. Tests reveal considerable increase in permeability of RC in comparison with the reference concrete. Both the water penetration depths and the permeability coefficients are increased in a manner that may be correlated with the increase in the replacement of natural aggregates by RCA. These increments are attributed to the high porosity of RCA.

Key words: permeability, porosity, recycled concrete, recycled concrete aggregate

INTRODUCTION

Recycled concrete (RC) may be considered as being porous concrete, having permeability values of up to twice that of normal concrete [1]. Its general behavior is a decrease in their physical and mechanical properties when the percentage of natural aggregate replacement by recycled concrete aggregates (RCA) is increased [1].

It is also known that the relationship between the aggregate porosity and water permeability of concrete [2] is of great importance for concrete durability because in most cases this relationship is the starting point for concrete deterioration.

For this investigation, RC containing RCA was tested in order to determine its water permeability. To accomplish this, five types of RC with different RCA contents were prepared, together with the concrete from which the RCA came.

EXPERIMENTAL DETAILS

Original concrete

In this study four m^3 of original concrete (OC) was used. The concrete was made in a mixer and was poured into wooden formwork frames measuring 0.40 m x 0.20 m x 0.10 m. Fifty cylinders measuring ϕ 0.15 m x 0.30 m and four cubes measuring 0.10 m x 0.10 m were also used to study the porosity and mechanical behavior.

Twenty-four hours after pouring, the specimens were removed from the formwork and submitted to a curing process for 150 days (see Table 1, where the specific characteristics of this concrete are given). The specimens were then passed once through a semi-fixed roller grinder with an inlet width of 0.45 m and a maximum outlet size of 0.025 m. Finally, the resulting material was classified into sizes (referred always in mm): 0-5, 5-10, 10-20, 20-25. The 5-10 and 10-20 fractions were used as RCA in this work.

Recycled aggregate and natural aggregate

The designation used by sizes was: for RCA, gravel 10-20 and fine gravel 5-10; and for the natural aggregate (NA), gravel 12-20 and fine gravel 5-12.

The criterion used for this fit was the compacted maximum density (which reduced the possible influences of different particle size). These were:

- For RCA the combination was 55% gravel and 45% fine gravel.
- For NA the combination was 70% gravel and 30% fine gravel.

Table 2 shows the properties of the aggregate used. The RCA used in this study can be considered as being within the RILEM recommendation for TYPE II RCA (absorption $\leq$ 10% and $D_s \geq 2000$ kg/m^3); for the Belgian recommendation they are GBSBII (absorption < 9% and $D_s > 2100$ kg/m^3); and in the Japanese case they comply with the absorption requirement ($\leq$ 7% and $D_s \geq 2200$ kg/m^3) in the fractions used [3, 4, 5, 6]. Consequently, the RCA employed in this study may be used in both plain and reinforced concrete if its application and factors of behavior are taken into account.

Mixture of recycled concretes

Due to the difficulty in determining the real W/C (water/cement) because of the high variation of absorption in the RCA, it was decided to use basic ACI 211.1 and ACI 211.2 mixture concepts proportioning with the following criteria:

(1) The substitution of RCA for NA was done using equal volume fractions with the following condition:

$$r = {RCA_{coarse}} \Big/ \left(RCA_{coarse} + NA_{coarse}\right) \qquad (0.00 \leq r \leq 1.00)$$

where: r = percentage of NA replaced by RCA, by volume; RCA_{coarse} = 55% recycled gravel + 45% recycled fine gravel; NA_{coarse} = 70% natural gravel + 30% natural fine gravel.

The percentages of the five samples of the studied RC were: r = 0.00, 0.15, 0.30, 0.60 and 1.00. As fine aggregate, 100% crushed natural limestone sand from the Garraf quarry, Barcelona, was used.

(2) The RCA showed an increase in absorption proportional to the time spent in water. For the mixture was taken 20 minutes of immersion,

with up to 97% fine gravel and 77% gravel, in all cases with comparison after 24 hours.

(3) The amount of water absorbed by the aggregate was taken into account separately, in addition to its wetness before mixing and the free water that formed part of the mixture. The above aspect is justified in criteria that were emphasized in a previous publication of the authors [7].

With the established mixing time and the required amount of water, the order of mixing the materials guaranteed (as far as possible) the immobility of the water and an improvement in the transition zone. The following sequence was adopted: (a) all of the coarse aggregate and water was introduced in the mixer; (b) these were mixed for 2 minutes; (c) the mixer was switched off for 3 minutes; (d) stages b and c were repeated twice; (e) the cement was introduced and mixed for 3 minutes; and (f) the sand was added and mixed for another 3 minutes.

The mixes obtained using the above criteria are given in Table 1. As can be seen, the variation in consistency and volumetric weight for the different percentages of aggregate replaced are within tolerable limits (slump 0.1 ± 0.03 m and concrete with volumetric weight normal).

Properties of the concretes

The tests on the different concretes comprised the study of the physical properties such as absorption, density, and porosity; and mechanical properties such as compression, tensile strength, and Young's modulus.

Tests of the physical properties of the concrete were carried done on 0.10 m x 0.10 m cubic specimens, while the mechanical tests were done on ϕ 0.15 m x 0.30 m cylindrical specimens with ages of 7, 28 and 90 days. Table 3 shows the results of the tests, in which the Spanish Norm Union [8, 9, 10, 11, 12, 13, 14, 15, 16, 17, 18, 19, 20] were used. Each value in the table is the average of two tests for physical properties and an average of three for the mechanical tests.

The sections below provide a summary of the behavior of the physical and mechanical properties:

The total porosity to water is the variable that shows the greatest difference between the RCA and NA and in the worst case reaches 2.8% for the NA and 14.9% for the fine gravel fraction of the RCA. As regards density, the RCA is lighter than the NA (with an average of 14% less in D_s and 9% in D_{sss}). The RCA shows an increase in density, which is directly proportional to the greater particle size. Finally, the differences between dry and dry surface saturated conditions are greater for the RCA than for the NA.

The absorption of the RC increases proportionally with RCA content, while their density decreases slightly. Water porosity, like absorption, increases proportionally with RCA content.

Simple compression decreases as the r factor increases for the studied ages: when $r \leq 0.30$, f´c is appreciably the same as the reference concrete and if the evolution of f´c is compared with the age of the RC, it is appreciated that its behavior is the same as the reference concrete, although the stress levels are of course lower. Indirect stress shows a similar evolution with age as with ordinary concretes. However, specimens with $r = 0.60$ and $r = 1.00$ show tensile strength values that are appreciably lower than the rest of the studied concretes for the age range under study. Finally, comparing results without reference to the age of the test, Young's modulus shows its minimum value for $r = 0.60$, closely followed by the value for $r = 1.00$. This property, therefore, shows a similar behavior to ordinary concretes.

Water permeability

As an initial definition, concrete permeability is the ease with which a fluid is able to pass through it (by means of permeable porosity or cracks) when it is subjected to a pressure gradient. It should not be confused with other fluid transport, such as diffusion or absorption, in which the causes may be the existence of concentrations or capillary rise.

Concrete permeability plays a significant role in most deterioration mechanisms because they are caused by penetration of the aggressive agent. The research that has been reported by Hansen and Bϕegh [21] with RC has indicated permeability increases of two to five times more than with reference concrete. They stated that there was a correlation between the W/C of RC and the RCA quality (W/C of OC). When the W/C of the RC is less (greater strength) than the W/C of the RCA, there is almost certainly a greater absorption and presumably a greater permeability (a dense matrix with porous aggregate).

Though the above information should not be ignored, the effect of the r factor within an RC has not yet been satisfactorily established. Wainwright and Cabrera [22] pointed out that the permeability of CR with $r < 0.75$ does not appear to be affected to any great extent. Therefore, in order to provide a more suitable understanding of the influence that the amount of RCA could have on the behavior of RC, the following experimental investigation was proposed.

The water permeability behavior in concrete was measured by means of three cylindrical specimens of ϕ 0.15 m x 0.10 m for each variable. Each of these cylinders was taken from the central part of a standard test cylinder of ϕ 0.15 m x 0.30 m, which had been kept in a curing chamber up to an age of 90 days (262 days for OC). Before starting to prepare the samples, the specimens were dried in an oven for 24 hours before proceeding with the test in accordance with UNE standard 83.309: 1990 [23].

The samples were prepared by covering (with a thickness of 0.003 m) the cylinder faces with an epoxy resin (Sikadur 31, which is habitually used for making concrete impermeable), so that the pressurised water was only able to penetrate the upper face of the specimens during the test (in the direction of concrete pouring). The epoxy resin that was employed was measured by weight in accordance with the manufacturer's recommendations. It consisted of a base (three parts) and a hardening agent (one part).

24 hours after the samples were made impermeable, they were placed inside the test chambers (three specimens per test) and the lower joint was sealed with epoxy resin. The test was then performed after a further 24 hours of joint hardening. Fig. 1 represents the section of a sample inside the test chamber, showing the water penetration and the criterion for determining it.

The times and pressures that were applied to the specimens were those established in accordance with UNE standard 83.309: 1990:

1) Stage: 100 KPa for 48 hours
2) Stage: 300 KPa for 24 hours
3) Stage: 700 KPa for 24 hours

When the four days had elapsed, the pressure produced by the water on the surface of the specimens was ceased and they were removed from the test chambers. In order to determine the penetration depth, two opposite generatrices of the specimens were cut through, which allowed a plane or profile to be generated through the cylinders.

Seven real readings of the penetration depth were made on each specimen every 0.02 m of thickness, plus another at the centre (0.03 m). These real penetration readings were transformed into equivalent readings by multiplying them by the distances between each measuring point, and finally averages were made of each individual specimen and every three specimens per variable (equivalent penetration). In a similar fashion, the maximum reading for each sample was recorded and averaged with the remaining two for each variable (maximum penetration).

Table 4 and Fig. 2 show the results of the equivalent readings for each specimen, the equivalent penetrations for each variable and the maximum penetrations obtained in the tests. As can be seen, the equivalent penetration shows significant increases (when $r = 1.00$ it is increased by 107% more than in the reference concrete), whereas the maximum penetration changes from 0.0104 m when the r factor = 0.0 to 0.0143 m for $r = 1.0$ (an increase of 37%). It should be noted that although the percentages in the maximum penetration differences are less than in the equivalent penetration, the real values vary by 0.0387 m for maximum penetration, while the equivalent penetration values only vary by 0.0052 m. The great difference between the equivalent and maximum penetrations may be explained by the fact that the RCA positions itself on the test surface, thus making the zone vulnerable and allowing water to pass through.

The hydraulic diffusion coefficient of the RC under study was determined by employing the equivalent penetration depth in accordance with the work of Kakizaki, Edahiro, Fujii and Nakase [24]; and also that of Ujike [25]. The adopted formula was:

$$\beta^2 = \frac{\alpha D_m^2}{4t\zeta^2}$$

where: β^2 = the hydraulic diffusion coefficient (cm^2/s), D_m = the equivalent penetration depth (cm), α = the constant relating the duration time t(s), when the hydrostatic pressure is applied (see Table 5) and ξ = is the constant related to the applied hydrostatic pressure (see Table 6)

Employing the previous formulae and the data proposed in the tables for the required constants, Table 7 shows the calculations that were performed to determine the diffusion coefficient of water for the RC under study. These values are also shown in Fig. 3.

In this respect the studies performed by Ujike [25] conclude that the use of RCA causes the diffusion coefficient of the RC to increase, and that the degree of this increase is affected by the quality of the RCA used, since diffusion is a property of the paste itself and of the properties of the transition zone in the interfaces surrounding the aggregates. This paper also states that, although the RCA is itself more permeable than the NA (because of the mortar adhering to the NA), the increase in the diffusion coefficient for water when RCA is employed is attributable to the changes that occur to the properties of the new transition zones in the RC.

CONCLUSIONS

Based on the research and results presented in this paper, the following conclusions are reached:

- The use of RCA causes an increase in the water permeability of RC. This increase is proportional to the replacement factor "*r*" and can reach values of up to twice that of the reference concrete.

- Although the variations in equivalent penetrations can be more or less equal (in terms of real readings), there is still the risk of maximum penetration at specific points. This penetration may be explained by the fact that an RCA locates itself close to the concrete surface, thus permitting the entry of fluids.

- The RCA has high porosity levels that can facilitate the flow inside the concrete.

- The previous differences that appear in the RC are attributed to the amount of paste adhering to the NA, which in turn may be affected by the quality (W/C) of the OC, by the conservation state of the OC and by the process used to produce the RCA.

- RC may show durability problems if suitable precautions are not taken, or if the design coefficients applied are not in accordance with its characteristics.

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Table 1 Mixtures used for recycled concrete

Component		r = 1.00	r = 0.60	r = 0.30	r = 0.15	r = 0.00	OC
Cement (kg/m^3)		400*					380**
Water (kg/m^3)		207.6					168
RCA (kg/cm^3)	Fine gravel (5-10)	406	258	134	69	0	-----
	Gravel (10-20)	497	315	164	84	0	-----
NA (kg/cm^3)	Fine gravel (5-12)***	0	268	488	604	710	252 (5-12)***
	Gravel (12-20)***	0	115	209	259	304	773 (12-20)***
Sand (0-5) (kg/m^3)***		662					784
W/C		0.52					0.44
Coarse A / Fine A (Vol.)		1.53					1.3
Additives (Plastifier)		-----					2.69

*: CEM I 52.5R UNE 80 301 96 RC/97. **: CEM I 42.5 R. ***: Limestone aggregate, Garraf quarry, Barcelona

Table 2 Properties of recycled and natural aggregate

Property	RCA			NA*		
	10-20	5-10	0-5	12-20	5-12	0-5
Dry specific gravity (kg/m^3)	2280	2260	2170	2570	2640	2570
Specific gravity (surface dry) (kg/m^3)	2410	2420	2350	2590	2670	2600
Water absorption (%)	5.828	6.806	8.160	0.876	1.134	1.49
Total porosity (%)	13.42	14.86	-----	2.70	2.82	-----
Shape coefficient	0.363	0.466	-----	0.364	0.576	-----
Longs indices	6	15	-----	8	19	-----
Modulus of fineness	7.2	6.2	3.8	6.9	5.0	3.3
Sand equivalent (%)	-----	-----	93.6	-----	-----	93.8
Particles < 200µ (%)	0.06	0.29	9.85	0.50	2.46	9.24

*: Limestone aggregate, Garraf quarry, Barcelona

Table 3 Mechanical and physical properties of recycled concrete

	Tensile strength (MPa)			Compressive strength (MPa)			Young's modulus (GPa)			Absorption (%)	Water porosity (%)	D_s (kg/m^3)	D_{sss} (kg/m^3)
Age* / Factor	7	28	90	7	28	90	7	28	90				
r =0.00	3.6	3.7	3.9	33.3	39.0	42.1	27.6	29.7	32.4	8.40	18.0	2130	2310
r =0.15	3.3	3.7	3.9	33.9	38.1	41.6	27.2	291	30.1	8.60	18.5	2140	2360
r =0.30	3.3	3.6	3.9	34.8	37.0	39.5	26.5	27.8	29.4	8.60	18.5	2150	2330
r =0.60	3.2	3.4	3.7	30.6	35.8	38.3	25.5	26.6	27.6	9.00	19.2	2120	2320
r =1.00	3.5	3.3	3.6	30.7	34.5	37.5	26.9	26.7	26.4	9.60	20.1	2090	2290
OC	3.2	3.8	---	35.2	38.4	---	33.0	33.7	---	5.90	13.4	2270	2410
OC**	4.1	4.1	4.2	45.1	45.4	47.0	35.2	34.5	34.6				

*: Days **: 172, 179, and 262 days of age

Table 4 Test results of water permeability of RC

Factor	Equivalent readings *	Equivalent penetration **	Maximum average penetration ***
r = 0.0	0.58	0.51	10.43
	0.51		
	0.44		
r = 0.15	0.53	0.58	11.35
	0.67		
	0.55		
r = 0.30	0.73	0.77	13.28
	0.85		
	0.73		
r = 0.60	0.68	0.82	8.67
	1.06		
	0.72		
r = 1.00	1.38	1.05	14.30
	1.02		
	0.76		
CO	0.45	0.40	5.75
	0.33		
	0.42		

*Each result is the average of 8 equivalent readings (cm).
** Equivalent reading average (cm).
*** Average of the 3 maximum readings recorded in the 3 tests per variable (cm).

Table 5 The α coefficient as a function of time duration "t"

t(s)	1	24x602	48x602	72x602	120x602	312x602
α	1	130.5	175.7	209.0	259.6	391.8

Table 6 The ζ coefficient as a function of the applied hydrostatic pressure

Po (MPa)	0.25	0.5	1.0	1.5	2.0
ζ	0.594	0.905	1.163	1.301	1.386

Table 7 The calculation of the diffusion coefficient of water for the RC under study

Factor	Equivalent penetration (cm)	1) Stage	2) Stage	3) Stage	Diffusion coefficient (cm^2/s) *
CO	0.4	7.20E-04	1.90E-04	6.76E-05	3.26E-04
r = 0.0	0.51	1.17E-03	3.10E-04	1.10E-04	5.30E-04
r = 0.15	0.58	1.51E-03	4.00E-04	1.42E-04	6.86E-04
r = 0.30	0.77	2.67E-03	7.06E-04	2.50E-04	1.21E-03
r = 0.60	0.82	3.03E-03	8.00E-04	2.84E-04	1.37E-03
r = 1.00	1.05	4.96E-03	1.31E-03	4.66E-04	2.25E-03

* Average of the three stages that make up a test.

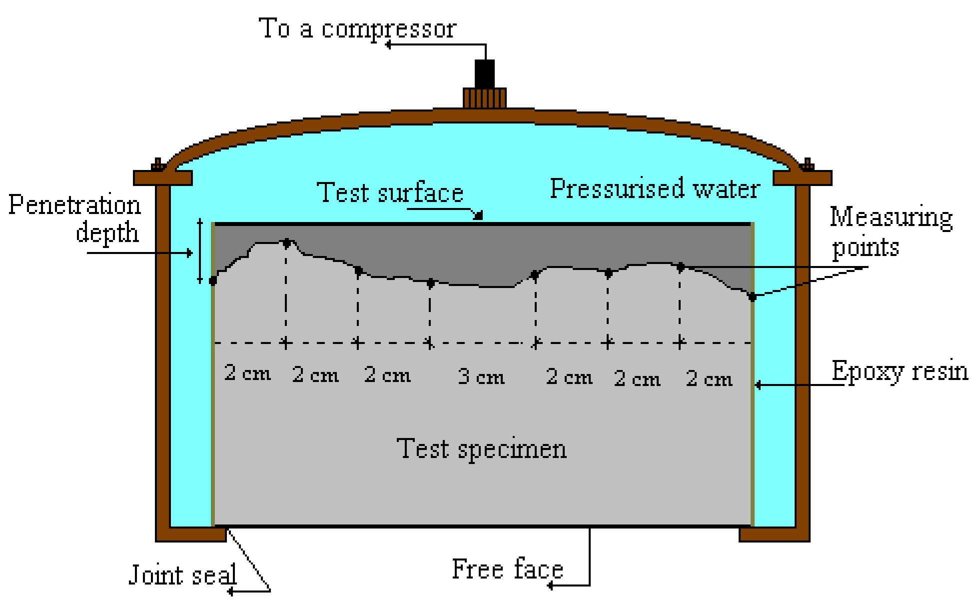

Fig. 1 Test set-up for the UNE 83.309: 1990

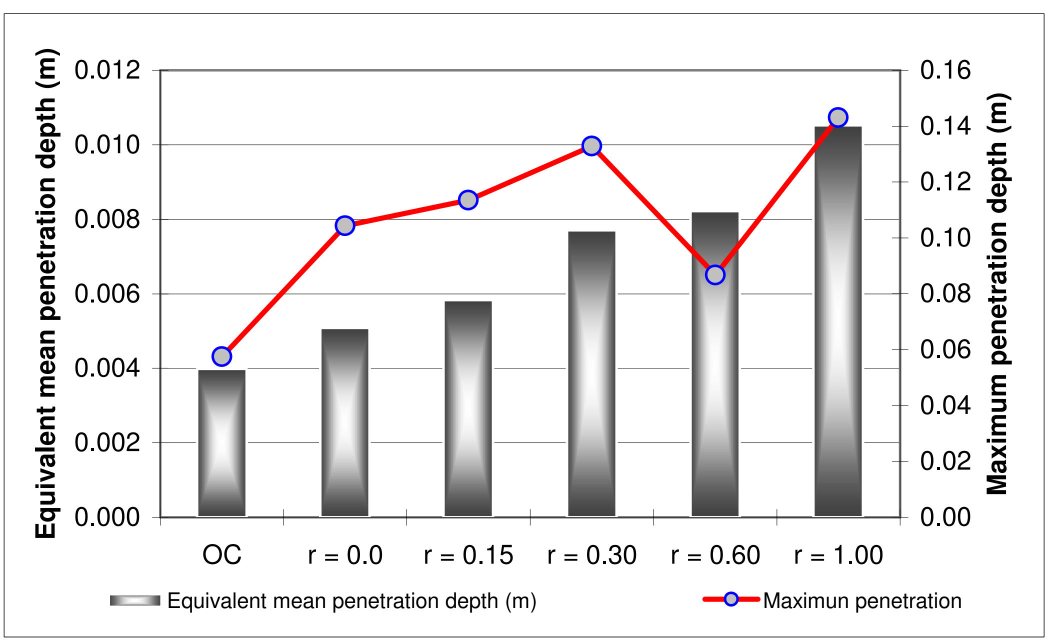

Fig. 2 RC behavior towards water permeability

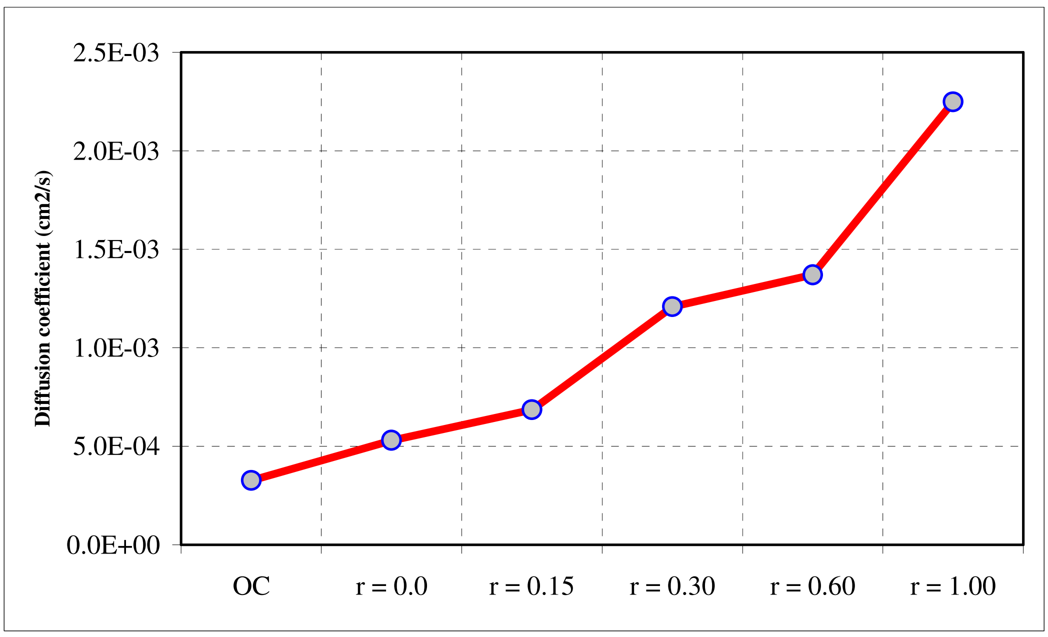

Fig. 3 Hydraulic diffusion coefficients for the RC under study